



Erosion assessment in the middle Kali Gandaki (Nepal) : A sediment budget approach

Monique Fort, Etienne Cossart

► To cite this version:

Monique Fort, Etienne Cossart. Erosion assessment in the middle Kali Gandaki (Nepal) : A sediment budget approach. Journal of Nepal Geological Society, 2013, 46, p. 25-40. hal-01196822

HAL Id: hal-01196822

<https://hal.science/hal-01196822>

Submitted on 16 Sep 2015

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

Erosion assessment in the middle Kali Gandaki (Nepal): A sediment budget approach

***Monique Fort^{1,3} and Etienne Cossart^{2,3}**

¹*Université Paris Diderot, PRES Sorbonne-Paris-Cité, GHSS, Case 7001,
F-75 205 Paris Cedex 13, France*

²*Université Paris 1-Panthéon Sorbonne (Geography)*

³*CNRS UMR 8586 PRODIG, Paris France*

*(*Email: fort@univ-paris-diderot.fr)*

ABSTRACT

Active mountains supply the largest sediment fluxes experienced on earth. At mountain range scale, remote sensing approaches, sediments provenance or stream power law analyses, collectively provide rough long-term estimates of total erosion. Erosion is indeed controlled by rock uplift and climate, hence by a wide range of processes (detachment, transport and deposition), all operating within drainage basin units, yet with time and spatial patterns that are quite complex at local scale. We focus on the Kali Gandaki valley, along the gorge section across the Higher Himalaya (e.g. from Kagbeni down to Tatopani). Along this reach, we identify sediment sources, stores and sinks, and consider hillslope interactions with valley floor, in particular valley damming at short and longer time scales, and their impact on sediment budgets and fluxes. A detailed sediment budget is presented, constrained by available dates and/or relative chronology, ranging from several 10 kyr to a few decades. Obtained results span over two orders of magnitude that can best be explained by the type and magnitude of erosional processes involved. We show that if large landslides contribute significantly to the denudation history of active mountain range, more frequent, medium to small scales landslides are in fact of primary concern for Himalayan population.

Key words: Himalaya, Kali Gandaki, erosion, landslide, sediment budget

Received: 16 January, 2013

Revision accepted: 25 April, 2013

INTRODUCTION

Solid particles transported by rivers dominate the mass transported out of continents to oceans. This is particularly true in steep, active mountains that supply the largest sediment fluxes experienced on earth, as estimated at global scale (Milliman and Syvitski 1992; Summerfield and Hulton 1994; Gaillardet and Galy 1999). At mountain range scale, total erosion is often estimated by using different approaches (stream power law, remote sensing approaches, or sediments provenance analysis), which provide rough long-term estimates. Sediment budgets are controlled by rock uplift and climate, hence by a wide range of erosion processes (detachment, transport and deposition), all operating within drainage basin units (hillslopes and talwegs). The time and spatial patterns of these processes can be quite complex, and should be documented at a more local scale to understand the succession of stages/sections of efficient sediment transfer with stages/sections of sediment storages, depending on landforms (both present and inherited ones) and water fluxes. Such patterns are commonly observed in the Himalayas, where the sediment

cascade is particularly efficient, as favoured by high, glaciated peaks, together with narrow valleys and steep hillslopes, in a monsoon-contrasted, climatic context (Fort 1987a; Fort and Peulvast 1995; Pratt-Sitaula et al. 2004). At local scale, landslides interaction with valley bottom may cause river channel diversions, short-lived dams and sediment traps, whereas remnants of ancient landslides may play an important role in the location of present instabilities and the control of sediment fluxes (Fort et al. 2009). Thus a sediment budget approach appears appropriate to understand the links between sediment mobilisation, transport, storage and yield (Slaymaker 2003) and to specify the varying pathways and processes involved in the sediment cascade (Fort et al. 2010a). In this paper, we aim to document what are the geomorphic processes that animate the sediment fluxes connecting sedimentary stores and what are the main coupling patterns we observe in such active mountain areas. The volumes of debris stored, eroded and exported by the Kali Gandaki in its middle reach (upper Myagdi and lower Mustang Districts, Nepal Himalayas) are assessed for the last thousands years up to present.

SEDIMENTARY BUDGET AND SEDIMENT CASCADE APPROACH

Our understanding of the denudation in the Himalayan Range is based on studies carried out at different time/spatial scales. Métivier et al. (1999) assessed the global denudation rate of the mountains of Central Asia via the resulting volumes of sediments stored in the large continental (Tarim, Qinghai) and marine basins surrounding them (Indus and Bengal fans, China sea, etc.). At the Himalayan scale, Galy and France-Lanord (1999) measured geochemical fluxes and sediments carried by rivers then trapped in foreland basins and marine fans. At watershed scale (i.e. Marsyangdi catchment, Nepal Himalayas), Garzanti et al. (2007) attempted at quantifying sand provenance through heavy minerals, hence defining the zone of maximum erosion, whereas in the same valley,

Pratt-Sitaula et al. (2004) tried defining the alternance of alluviation events and incision stages on the basis of fluvial terrace, straths and radiometric dating (Pratt-Sitaula et al. 2007). By analyzing the relationships of sediment transport with daily river and precipitation data, Andermann et al. (2012) estimated the suspended sediment denudation rate of the Kali Gandaki to be 2.8 mm/yr, the largest among the major drainages of Nepal.

Our study focuses on shorter time span and spatial scale. The approach is based on two complementary concepts, sediment budget and sediment cascade through the geomorphic system, which can be subdivided into sub-systems (e.g. rockwalls, hillslope, valley bottom). The concept of sedimentary budget (Fig. 1) implies the identification of sediment sources, sediment stores and

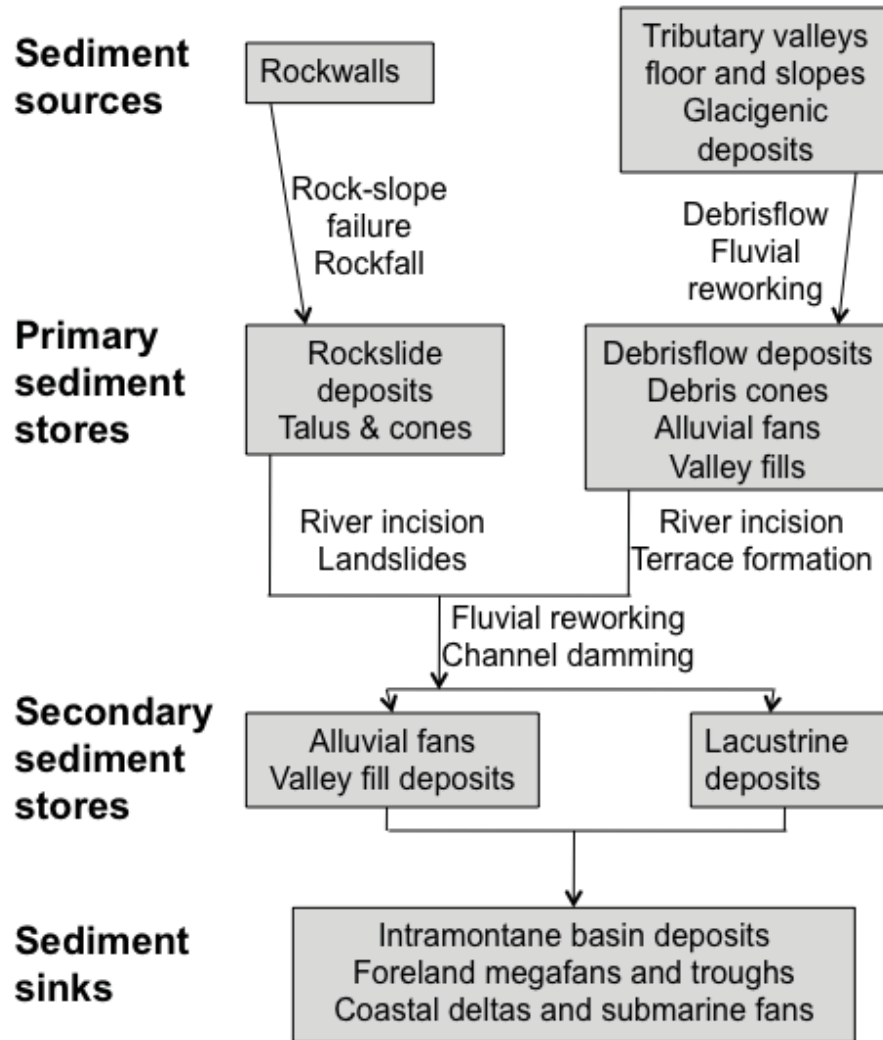


Fig. 1: Sedimentary budget concept. The grey boxes represent sediment stores. Sediment fluxes connecting stores are animated by different geomorphic processes.

sinks. In Himalayan valleys such as the Kali Gandaki valley, most sediment sources are rocky mountain slopes (rockslope failures and rockfalls, or/and rock weathering) adjacent to the valley floor, and tributary valleys (debris derived from rockslopes and/or from inherited glacigenic deposits). Set into motion by sismo-tectonic and/or climatic events, the loose debris is reworked and transported by slope processes (landsliding) or fluvial processes, and may be deposited in primary sediment stores, either as landslide debris or as secondary stores such as alluvial or lacustrine fills. The different sediment sources and stores are connected through sediment cascades (Fig. 2), i.e., debris and water fluxes that transit from the different elements of the geomorphic system: mountain slopes, gullies, valley floor, and river channel, at different spatial and time scales. These connections may be alternately efficient or not, and this functioning is documented through the estimation of the volumes of debris eroded and exported by the Kali Gandaki since the formative failures that impounded the valley at different sites.

RESEARCH AREA

We focus on a specific reach of the Kali Gandaki valley (Fig. 3), i.e., from downstream of Tatopani (Myagdi District) up to Kagbeni (Mustang District), from the transition between the Lesser and Greater Himalayas (Upreti and Yoshida 2005) up to the metasediments of the “Tibetan series” (Colchen et al. 1986). More specifically, from Tatopani up to the north of Dana, the upper Lesser Himalayan sequences display an alternation of slates-phyllites bands with quartzites, affected by various mylonitic facies while approaching to the MCT zone. Further to the north, the Higher Himalayan Crystalline (HHC) sequences (including mica-gneisses, calcareous gneisses and augen gneisses) are taking over up to Kalopani, where the low-grade Tibetan Sedimentary Sequence (TSS), mostly metasedimentary marbles, predominate and are deformed by north verging folds (Upreti and Yoshida 2005; Colchen et al. 1986). This Kali Gandaki section spans across two major structures: to the south, the Main Central Thrust (MCT), between the upper Lesser Himalaya and the lower part of the Greater Himalaya; to the north, the North Himalayan Detachment Fault (NHDF), otherwise called South Tibetan Detachment System (STDS), a prominent family of normal faults along the contact between HHC and TSS affected by a down to the north displacement (Burchfield et al. 1992; Godin 2003).

Geomorphologically, the Kali Gandaki valley is mainly V-shaped, with very narrow gorge segments controlled by N10° oriented dip slopes (dip gradient varying between 30° to nearly 90°) alternating with limited wider areas, bounded by unstable, debris-covered slopes (slope gradient

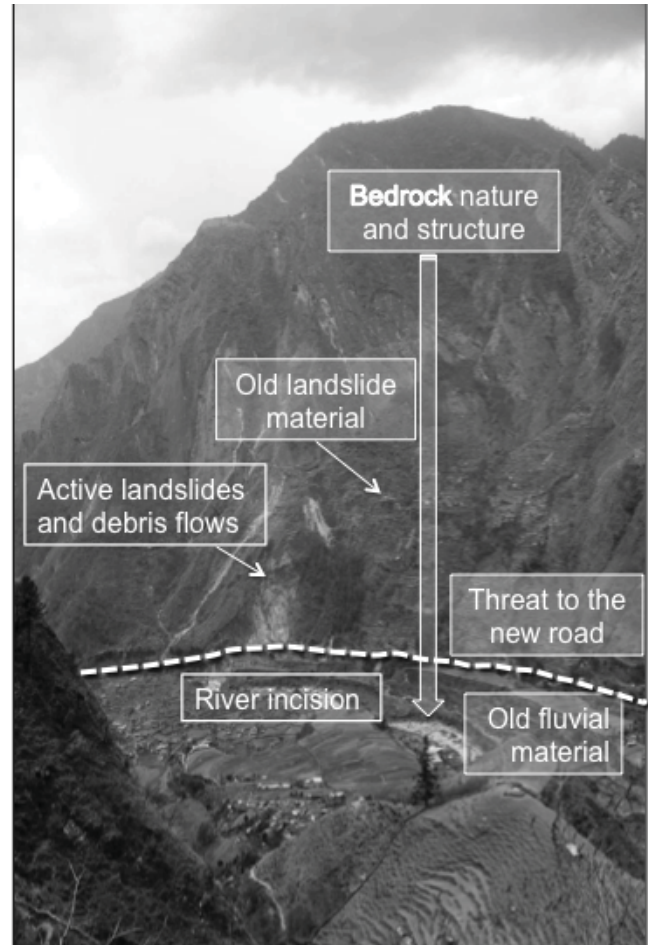


Fig. 2: Sediment cascade concept, including upslope-to-downslope fluxes, and upstream-to-downstream fluxes.

<30°) corresponding to older landslide material most prone to be re-mobilized (Fort 1987b; Fort et al. 1987; White et al. 1987). The valley bottom displays a narrow floor with discontinuous patches of aggradational terraces of late Pleistocene and Holocene age (Dollfus and Usselman 1971; Fort 1974; 1993; 2000; Yamanaka and Iwata 1982; Monecke et al. 2000); in addition very discontinuous patches of old alluvial formations can still be found perched several hundred meters high above the present river bed (Dollfus and Usselman 1971; Fort 1974; 1993), suggesting the magnitude of river incision after their deposition.

The valley appears as a fragmented river system (sensu Hewitt 2002) interrupted by a series of landslides and/or large debris flow fans that temporarily blocked the sediment conveyance of solid discharge to the downstream reaches (Fig. 3). From north to south, the main landslide barriers are as follows. The prehistoric, giant (10^9 m^3) Dhampu-Chhoya rock avalanche (Fort 1974, 2000) dammed the upper Kali Gandaki, with complex relationships with the Late

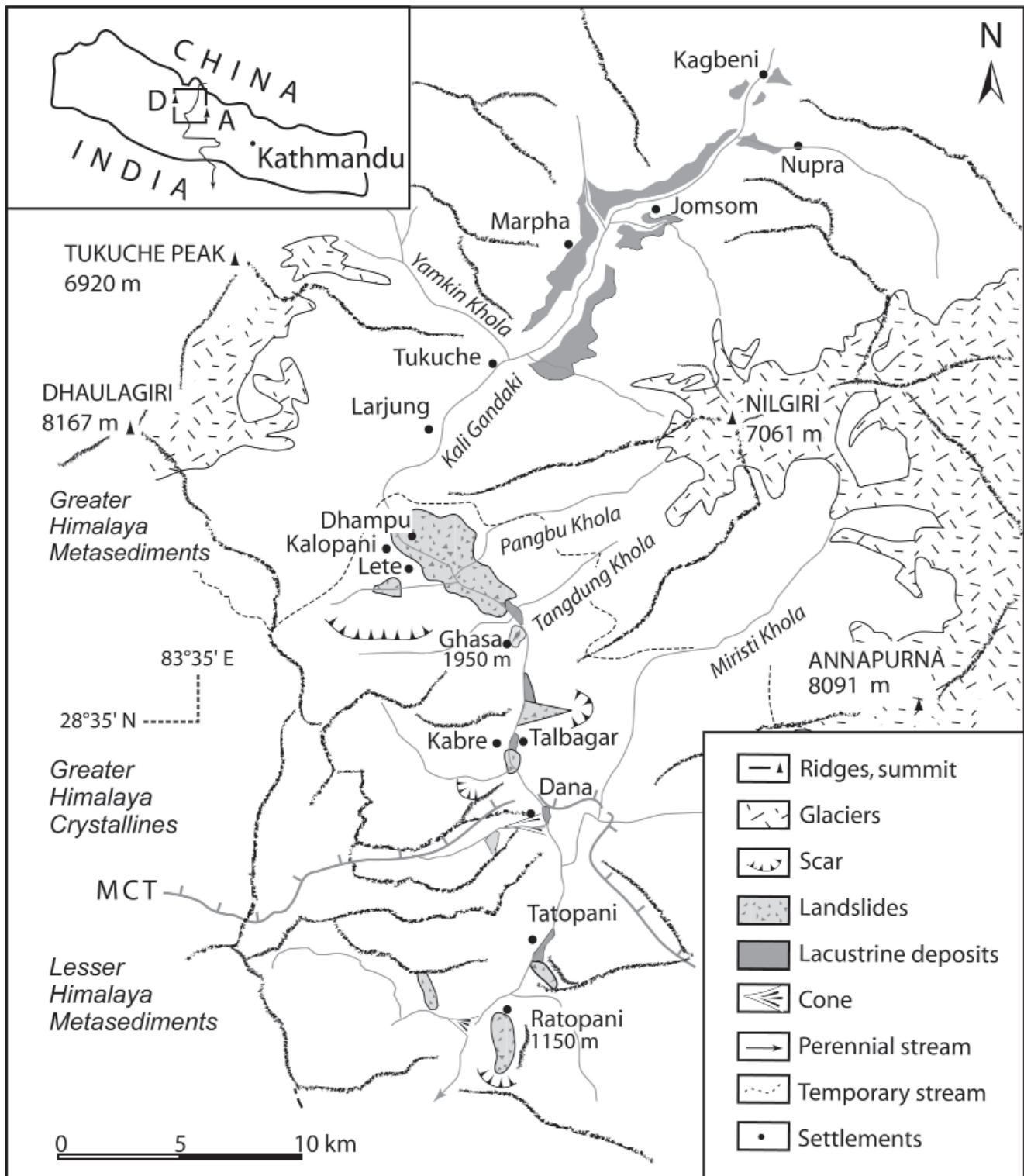


Fig. 3: The middle Kali Gandaki River and location of main studied features.

Pleistocene ice tongues derived from the Dhaulagiri (8167 m) and Nilgiris (7061 m) peaks. Both the rock avalanche and glaciers controlled the former “Marpha Lake” deposits that extend upstream from Tukuche up to Kagbeni (Fort 1980; Iwata et al. 1982). Adjacent to the Dhampu-Chhoya rock avalanche, the Kalopani one correspond to a more recent event, the distal debris of which having formed the widespread Lete-Kalopani cone. Further down the valley is interrupted by the Ghasa landslide (postdating the Dhampu-Chhoya one; Fort 2000; Zech et al. 2009), then by the undated Pairothapla-Talbagar and Kopchepani landslides dams (Fort et al. 2010b). Other modern features are still actively, partly and/or temporarily impounding the valley: the two debris cones of the Ghatte (Dana) and Dhoba kholas, both supplied by the right bank tributaries of the Kali Gandaki, and the 1998 Tatopani landslide (Fort et al. 2010b). In addition, large sediment storages in the form of terraces are found all along the studied area: we will refer mostly to the large set of terraces developed at the junction between the Miristi Khola and the Kali Gandaki (Monecke et al. 2000).

METHODS

Sediment is routed through storage reservoirs: sediment fluxes are inferred from the variation of the volume of the reservoirs, according to their age when available. On the basis of diachronic (1974-1982-1993-2000-2008) geomorphic surveys and field mapping, along with aerial photographs, topographic map analysis, and with the recent help of DEM facilities, we reconstructed the extent of the landslide deposits, the nature (lacustrine and alluvial) and volume of the sedimentary traps, and the evolution of the landslide masses. We established the cross section of landslide masses in the valley and characterized the material (size, sorting). The volume of sediments released by the mountain slope was assessed, including the debris cones (the very dam), and the sedimentary wedges resulting from superficial reworking and redistribution of debris. We also estimated the volume of debris eroded and exported by the Kali Gandaki since the failure. All sediment export calculations were based upon simple geometric landforms (Campbell and Church 2005): talus, cone, etc. Basic measurements (height, width, etc.) were adapted to the field area, and surveyed with a Leica laser telemeter and hand-help GPS.

RESULTS

We present below results that include the most prominent sediment storages of the considered valley section. We selected them according to their type, volume and age, according to previous investigations.

Dhampu-Chhoya rock-avalanche, and the “Marpha Lake”

We consider here the upstream part of the Kali Gandaki valley, north of Ghasa up to Kagbeni. It is difficult to single out one feature, because the Dhampu-Chhoya rock avalanche, together with the legacies of the “Marpha Lake”, cannot be totally understood without considering the complex interactions between these two features and the last Quaternary glaciation (Fig. 4).

The giant, persistent rock-avalanche dam of Dhampu-Chhoya is largely described and commented in Fort (2000). It should be mentioned that this rock-avalanche corresponds to an event different from the more recent Kalopani debris-avalanche cone and fan (as in Weidinger 2006) derived from Sarpang Dhuri, whose debris and associated deposit are cut-and-fill into the older Dhampu-Chhoya rock-avalanche runoff.

The apparent areal extent of the Dhampu-Chhoya rock-avalanche is about 10 km² (Fig. 4). It reaches a thickness of at least 300 m, as observed along the left bank of the Kali Gandaki between Chhoya and Kaiku (Fig. 4C). The base of the material, mostly hidden by scree and rubble covering the foot of the slope, is below or close to the level of the present bed of the river, and suggests a minimum displaced volume of approximately 1 km³. The failed mass is made of granitic gneiss material, hence is derived from the right side of the Kali Gandaki river, namely the Kaiku ridge (~3300-3400 m). The latter is much lower than the Bandarjung Turture Danda (~4000 m) west of Ghasa while it should be higher as regards to the geological and morphological structure of the Higher Himalaya. This large collapse of the Kaiku ridge was most probably triggered in relation to the activity of Northern Himalayan Detachment Fault (Fort 2000; 2011). According to recent dating, it was emplaced about 30,000 years ago (Zech et al. 2009; 10Be, R. Braucher and D. Bourlès, personal communication; Fort et al. in prep.) across the narrow gorge of the Kali Gandaki River, hence ensuring dam stability and longevity (Fig. 4A and C), and persistent aggradation by the Kali Gandaki, associated to a braiding pattern. The dates recently obtained make the geomorphic evolution of this valley section more complex than expected, as discussed below.

Indeed another important event was the development of a large lake upstream, the Marpha Lake (Fort, 1980) that extended more than 23 km in length, flooding the entire Kali Gandaki valley and its tributaries as inliers from Tukuche up to Kagbeni (lake top at about 3000 m). In the type locality (Marpha), the depth of lacustrine deposits is close to 200 m (Fort 1980), probably a minimum thickness (Fig. 4B). Dates of lacustrine sediments between Marpha and Syang span

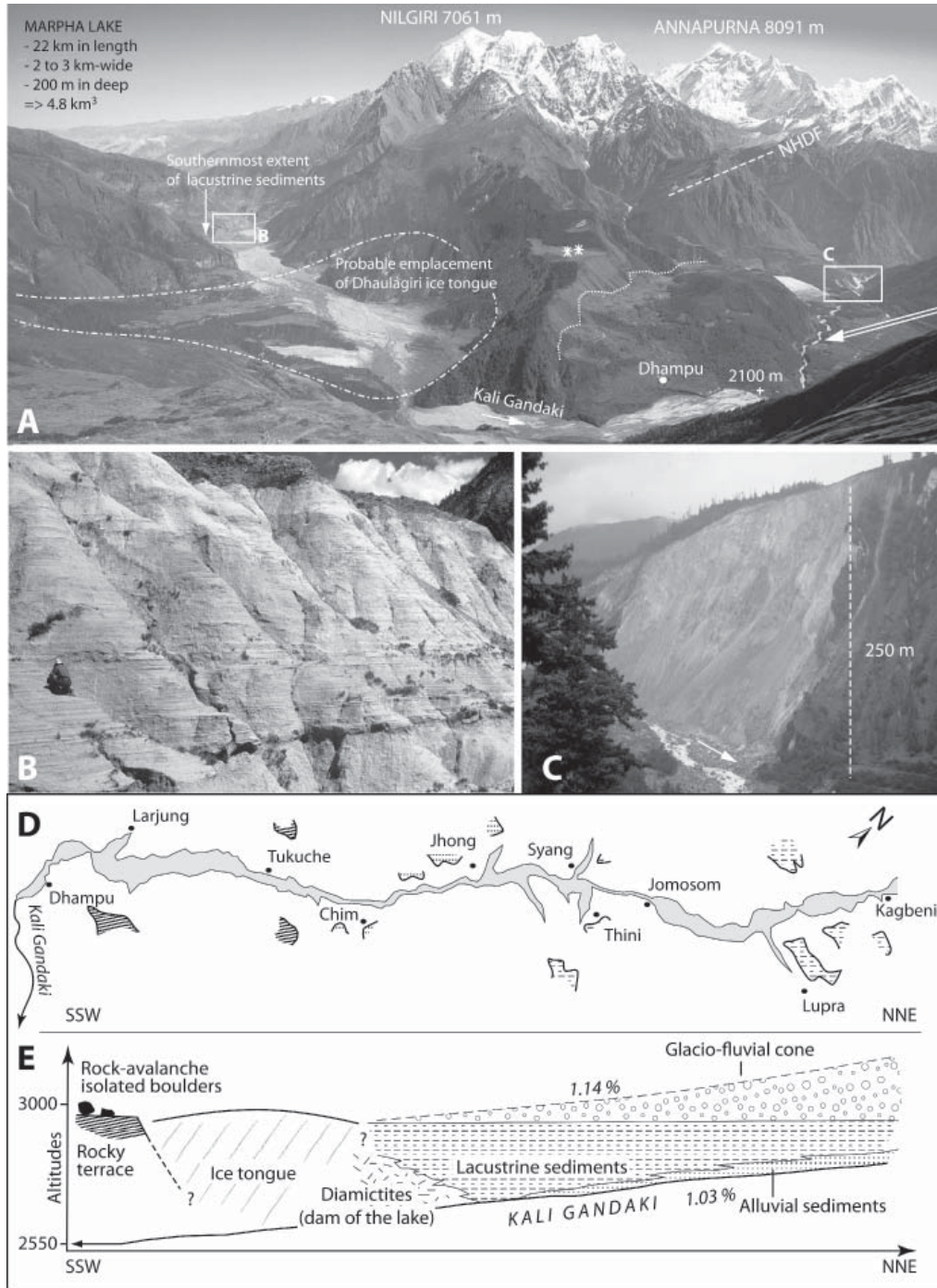


Fig. 4: The large, prehistoric Dhampu–Chhoya rock avalanche. (A) View from the east face of Dhaulagiri). The collapsed mass (several failure events are not excluded) failed along the North Himalayan Detachment Fault (NHDF) and blocked durably the Kali Gandaki River; the ice tongue issued from Dhaulagiri (8172 m) might have controlled the lake level. Asterisk indicates the location of 10Be sampling. (B) Lacustrine sediments, Marpha section; (C) Section of the Kali Gandaki left bank exhibiting the fractured rock-avalanche material; (D) The present braided channel of the Kali Gandaki (in grey) and perched remnants of lacustrine-alluvial deposits, as superposed in (E) Lacustrine sediments derived from upstream and from glaciated tributary valleys, with interfingering with retrogressive alluvial fan facies, until Kali Gandaki alluvial deposits prograde downstream during and after complete filling of the lake.

over stages of the Last Glaciation: according to Baade et al. (1998) and to Baade (2000), the lake was in existence from 56.4 ± 6.94 ka up to 32.7 ± 3.8 ka BP (OSL dates), a time span large enough that might have included two lacustrine stages as suggested by Iwata (1984). Clearly however, the lacustrine episode ended soon before the Dhampu-Chhoya rock-avalanche failure.

This discrepancy in the dating of both lacustrine and failure events raise the issue of the nature of the lacustrine dam: rock-avalanche, as initially thought (Fort 1974; 1980; Baade 2000) or possibly a glacier tongue (Fort 2000)? During the last glaciation (Fort 2004), a glacier tongue issued from the east face of Dhaulagiri (8167 m) most probably reached the Kali Gandaki valley bottom (i.e. calcareous breccia plastered along the left bank of the Kali Gandaki, north of Dhampu) (Fig. 4A). Yet, a glacial tongue is not resistant and persistent enough to dam and contain such a large lake (>4 cubic kilometres; Fort 2000). In order to match the level of the lake together with morphological and sedimentary remnants on the one hand (Fig. 4D and 4E), with the OSL dates of lacustrine sediments and ^{10}Be dates of Dhampu-Chhoya rock-avalanche on the other hand, we end up with the following hypothesis: another massive rock-failure, older (>30 ky) than the Dhampu-Chhoya one that we dated, might have formed the initial dam, whereas the adjacent Dhaulagiri glacier tongue controlled the lake level hence the lake sedimentation. Alternatively, we may question the dating methods and their reliability, and/or consider the possibilities of sediment reworking or weathering that might have brought more uncertainty on the exact timing of these different events. The fact that both Zech et al. (2009) and our team (together with R. Braucher and D. Bourlès) have obtained consistent cosmogenic dates, from different samples and different laboratories, provides very good evidence of a chronologically, well constrained Dhampu-Chhoya rock-avalanche event, i.e. about 30,000 years ago. Conversely, dating of lacustrine sediments has not been crosschecked to date, and some uncertainty cannot entirely be ruled out.

From the above discussion, the assessment of sediment budget and fluxes should be established as follows. If incision of the lacustrine sediments could not began before 32.7 ± 3.8 ka BP (youngest age of lacustrine deposits), incision was further delayed by the Dhampu-Chhoya rock-avalanche that occurred at about 30 ka ^{10}Be . In addition, we reasonably assumed that exportation of lacustrine sediments was controlled by the Dhaulagiri ice-tongue thickness, and by progressive and/or fluctuating restoration of full conveyance when the Kali Gandaki valley bottom became ice-free, i.e., after the Last Glacial Maximum. We can consider it occurred at $\sim 18\text{--}24$ ka (i.e. Marine

Oxygen Isotope Stage 2, or MIS-2) as in the other parts of the Himalayas (Owen 2009), without ruling out other smaller glacier advances during Holocene that might have temporarily impounded sediment export. The emplacement of the former Dhaulagiri and Tukuhe Peak ice tongues is now occupied by younger, thick debris-flow deposits underlying the terraces and cultivated fields of Larjung and Khobang (Fig. 5).

Nowadays, most of the lacustrine sediment is removed, and valley incision by the Kali Gandaki River formed a series of stepped terraces (downwasting of the ice tongue? stages of rock-avalanche dam incision?) cut into the lacustrine deposits, with abundant supply of debris from the slopes (Fig. 6). Near Kagbeni (2900 m), the lacustrine beds ping out and are progressively replaced by the fluvio-deltaic prism that underlies the >200 m high terraces of the Kali Gandaki, ^{14}C dated by Hurtado et al. (2001). Assuming a minimum lake volume of 4 cubic kilometres and a maximum time span of 20 ka (no incision before), we calculated that more than 80% of the former lacustrine sediment is eroded, giving a large figure of sediment removal (min. exportation rate of $200,000 \text{ m}^3/\text{yr}$). Indeed, this incision rate is quite dramatic, yet favoured by the very erodible type of sediment (silts). Export nowadays is very limited, and mostly depends on catastrophic shifting of the Kali Gandaki from one side to another side of the valley.

Pairothapla-Talbagar debris avalanche

The Talbagar debris avalanche, also referred to as Pairothapla, is located on the left bank of the valley (Lat. $28^\circ 34' 14'' \text{N}$ and Long. $83^\circ 38' 25'' \text{E}$, southernmost Mustang District) along a 2000 m high mountainslope, cut into the Greater Himalayan crystallines (Colchen et al. 1986) where weaker biotite and hornblende rich bands alternate with steeper calcareous gneiss (Upreti and Yoshida 2005). The Pairothapla-Talbagar debris avalanche (about 16 million m^3) dammed the Kali Gandaki gorges at their narrowest, probably a few centuries ago according to the thin weathering soil horizon (dating under progress), hence forced the sedimentation upstream with a resulting lake of estimated 9-14 million m^3 in volume (Fort et al. 2010b). Lacustrine silts and sands are coarsening upstream ward and laterally with alluvial and slope sediment influxes. The left bank of the Kali Gandaki river displays a very actively eroded, 100 m thick debris avalanche section. It is composed of a diamicton including very large blocks ($>350 \text{ m}^3$) and fine crushed, gneissic material composed of the superposition of two debris avalanche events, of an assumed age of four hundreds and one hundred years respectively (see discussion in Fort et al. 2010b). The Kali Gandaki River restored its

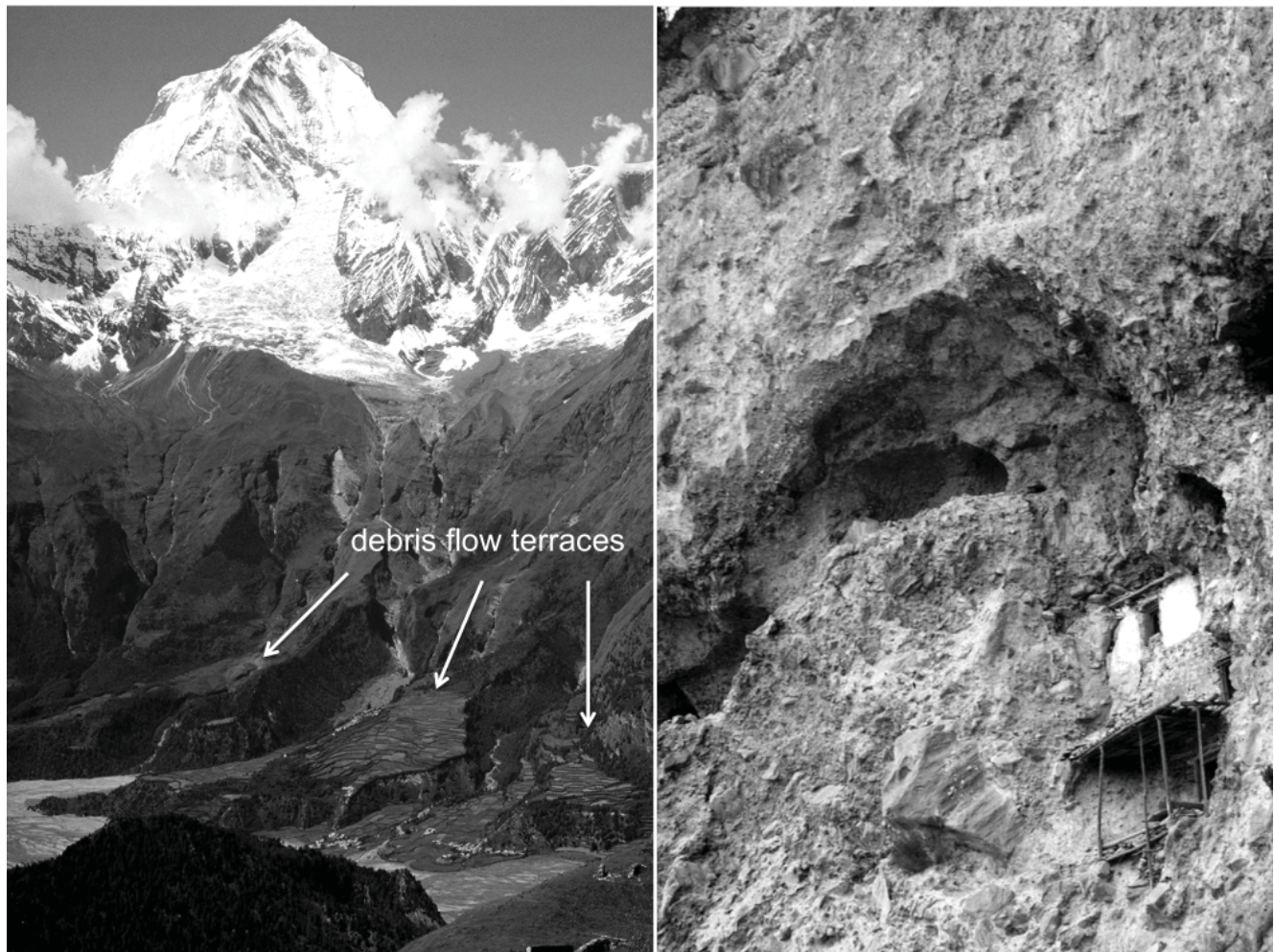


Fig. 5: East face of Dhaulagiri (8172 m), with debris-flows terraces of Larjung and Kobang (left) at ~2500-2600m, and detail of debris-flow material near Khobang (right).

continuity by cutting through the debris then incising the bedrock underneath, with the development of a spectacular epigenetic gorge.

Downstream, after the breaching of the first dam, a large (11 million m³) sedimentary wedge formed that is now dissected (remnant: 4 million m³). The breaching of the second dam following a second debris avalanche event and subsequent valley damming, led to the formation of new cut-and-fill terrace (2.3x10⁶ m³), a large part of it is already removed (present remaining volume: 0.8x10⁶ m³). The synthesis of our calculation (Fig. 7) shows that more than 63% of the initial volume of the upper terrace has been removed, a figure that represents a rate of combined incision-exportation of about 6000 m³/yr, assuming a 400-year age for the formative event. For the lower terrace (100-year old), the percentage of removal is about the same (60%), yet the combined incision-exportation rate is

much higher (13,000-15,000 m³/yr). The fact that this rate is calculated on a shorter period is for us good evidence that most of the erosion work is instantaneously carried out during the outburst of landslide dams, so that coupling between mountain slopes and river is efficient and, finally, the work accomplished by the river is steadier between two “extreme” events.

Alluvial examples

Two alluvial examples, the first one along a large tributary (Ghatte khola) debris flow cone built up at the junction with the Kali Gandaki, and the second one corresponding to a large set of Holocene and modern terraces built at the Miristi/Kali Gandaki confluence, show that sediment stores related to fluvial/torrential transport and deposition may also be quite impressive.

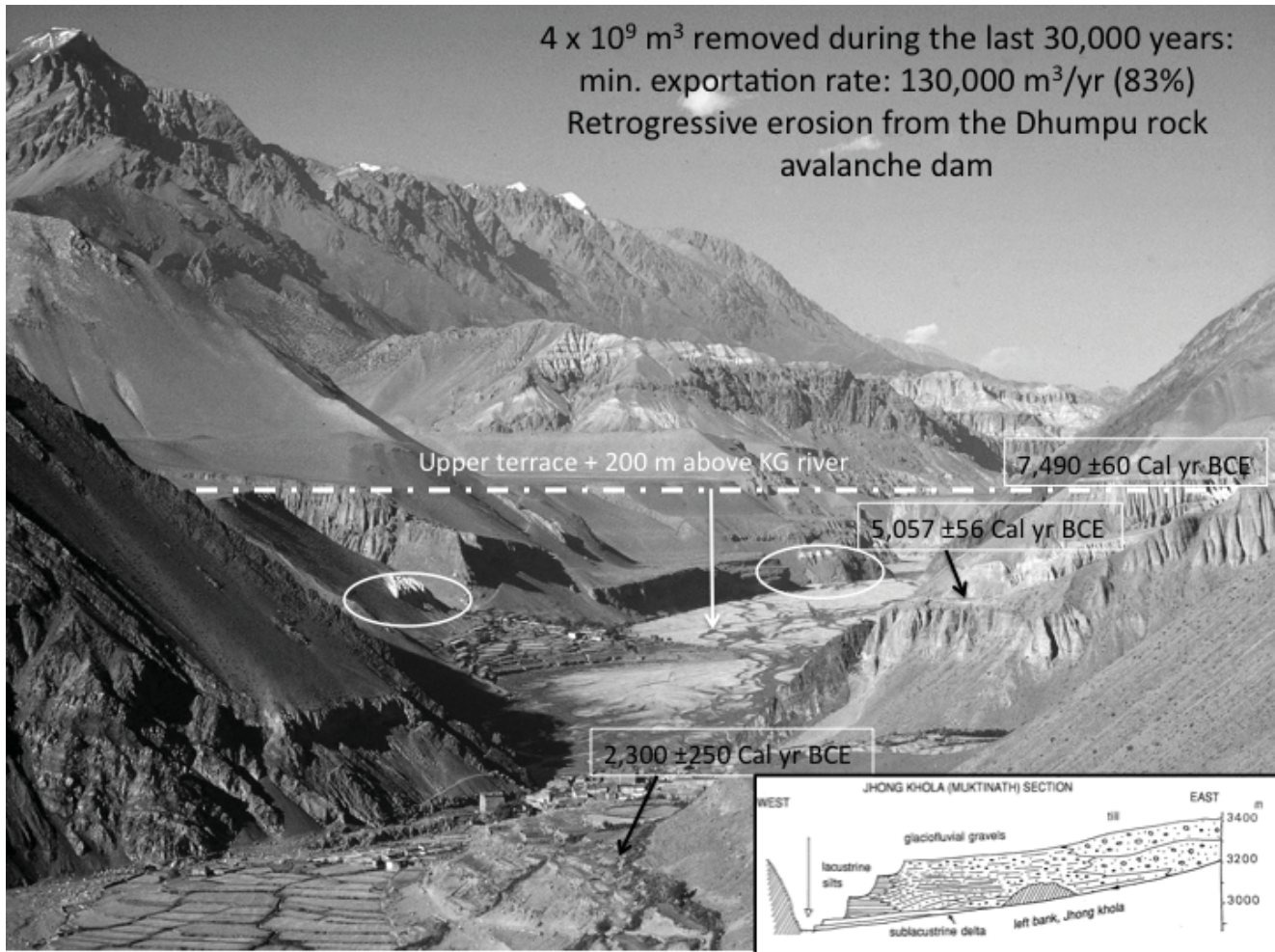


Fig. 6: Morpho-sedimentary pattern near Kagbeni and calculated Holocene sediment removal rates; ^{14}C dates from Hurtado et al., 2001. Box: section along the Jhong khola, left tributary of the Kali Gandaki, from Fort 1980).

The Ghatte khola, a right bank tributary of the Kali Gandaki, drains a small (7.8 km^2), steep (37%), east-west elongated catchment, characterised by a pronounced asymmetry striking perpendicular to the northward general dip of the Himalayan structures (Fig. 8 A). At the junction with the Kali Gandaki, the Ghatte khola has built up a large debris fan (1.5 km wide and 2 km long). Developed in the upper Lesser Himalaya Formation close to the MCT zone (Colchen et al. 1986; Upreti and Yoshida 2005), the 70° steep counter dip scarps (mostly quartzites, left bank) of the Ghatte catchment contrast with the $>40^\circ$ steep dip slopes (aluminous schists, right bank). These latter are affected by active translational slides that are most often triggered by heavy cloudbursts distinctive of the pre-monsoon season (Fort 1974). Depending on their size, the slide masses may clog for a few hours the upper narrow valley of the Ghatte stream upstream, until a sudden, landslide lake

outburst flood (LLOF) occurs and generates sporadic, sometimes fairly destructive debris-flow events (Fort 1974; Fort et al. 2010b) (Fig. 8B). These latter have caused the progressive aggradation of the confluence debris-flow fan, encroaching over the Kali Gandaki alluvium, as exhibited along the left bank of the fan nearby the village of Dana. Modern erosion along the fan banks caused by successive LLOFs (they occur every two-three years) together with aggradation of the channel bottom are both good evidence of the transient sediment flux and continuous reworking of sediment storages by the river. The fact that the Ghatte khola debris fan is in direct connection with the Kali Gandaki river allows a high rate of removal during and just after the monsoon season, with an export rate varying between 30% and more than 60% of the original landslide debris, hence on stream discharge.

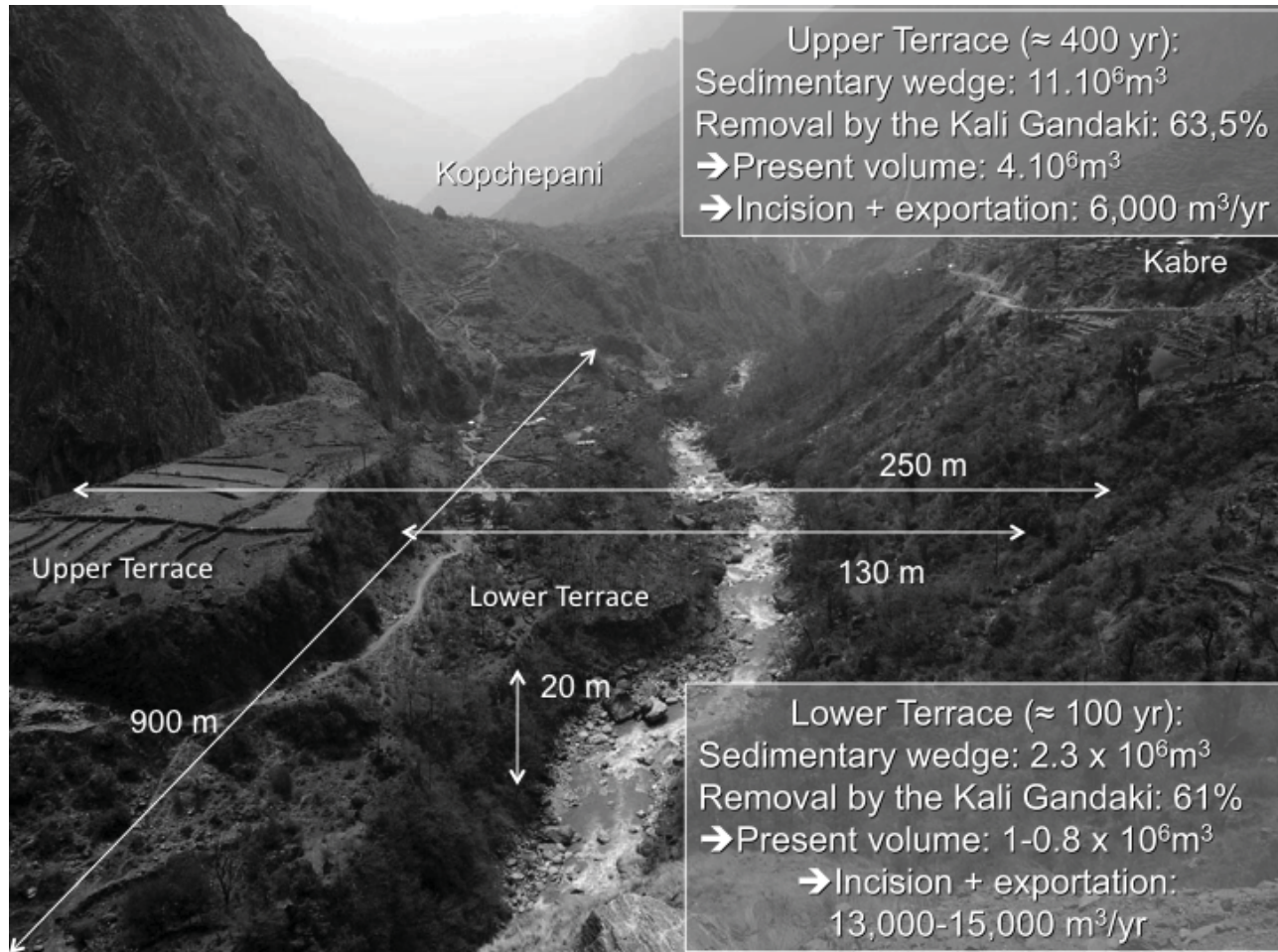


Fig. 7: Sedimentary wedges downstream of Pairothapla-Talbagar debris avalanche and later sediment removal.

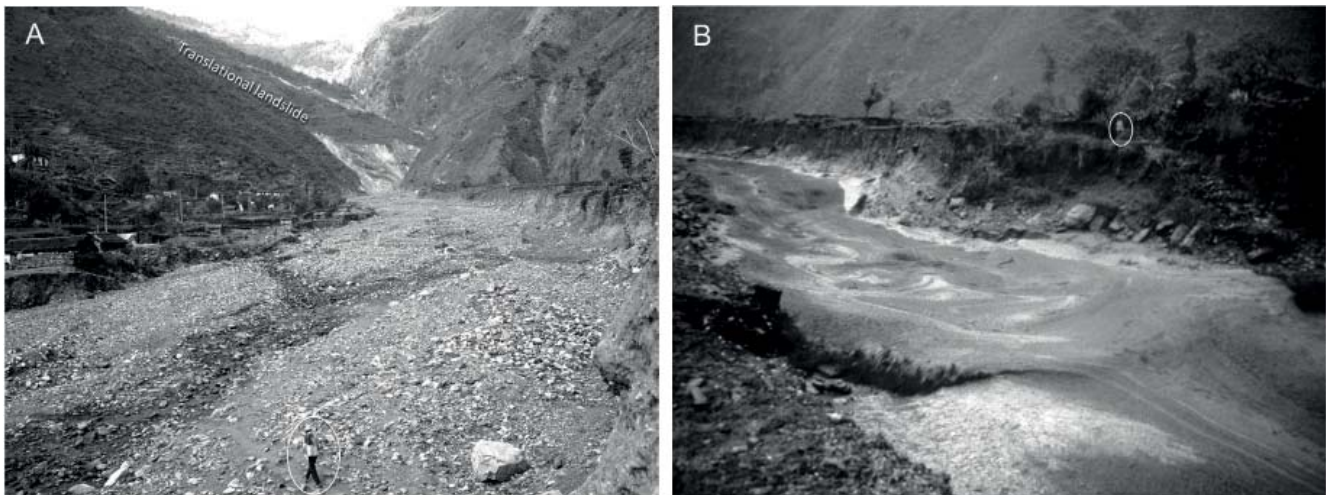


Fig. 8: (A) Asymmetric Ghatte khola watershed, characterized by rapid sediment fluxes with time in response to landslide events occurring upstream, hence causing both changes in channel width (15m in 1974, 35m in 2009) and in bed surface morphology (short term alternation of aggradation/incision stages, in a regional trend of river incision). (B) Debris flow event as witnessed in May 1974.

The second example is the set of Holocene and modern terraces (max. relative elevation +20 m) built up at the Miristi/Kali Gandaki confluence; it has been extensively described and dated by Monecke et al. (2001). These authors show that these terraces are the result of complex cut-and fill aggradation, with lithofacies evidencing an alternation of fluvial and debris flows units. They interpret these debris flows as sedimentary responses to climate changes in connection with stages of glacier melting and/or final deglaciation, without totally ruling out the possibility of being a response to earthquake or glacial-lake outburst floods. Alternatively, our observations in the upper Miristi catchment suggest the debris flow units might also be a response to landslide dam outburst floods that occurred in the upstream part of the Miristi khola and its tributaries (Ghaleti khola) (Fort 1993; Zech et al. 2009). Whatever the interpretation of these debris flows events, it is important to note that a significant part of the original terrace deposit representing a volume of about $21 \times 10^6 \text{ m}^3$ has been removed by further incision and lateral shifting of the Kali Gandaki river (Fig. 9): we estimated the volume removed to be

~60%, that would represent an average rate of $1260 \text{ m}^3/\text{y}$, a value that indeed does not represent the reality of what has probably been operated by sporadic, impulsive flood events, as suggested by the last example.

1998 Tatopani landslide

A last example corresponds to the 1998 Tatopani, rainfall triggered landslide that affected the quartzites and phyllites (mostly green chloritoschists) of the upper part of the Lesser Himalaya formations (Sikrikar and Piya 1998). This slope has experienced a series of retrogressive, large scale, failures during the recent decades (Fort et al. 2010b), and is affected in depth by slow rock creep (Voelk 2000). In 1998 however, the failed mass was significant enough to impound the Kali Gandaki flow for a few hours (Fig. 10).

The volume of the landslide ($1.1 \times 10^6 \text{ m}^3$), landslide dam ($0.7 \times 10^6 \text{ m}^3$) and lake ($1.5 \times 10^6 \text{ m}^3$) were assessed by Fort et al. (2010b) together with the volume of the eroded breach by

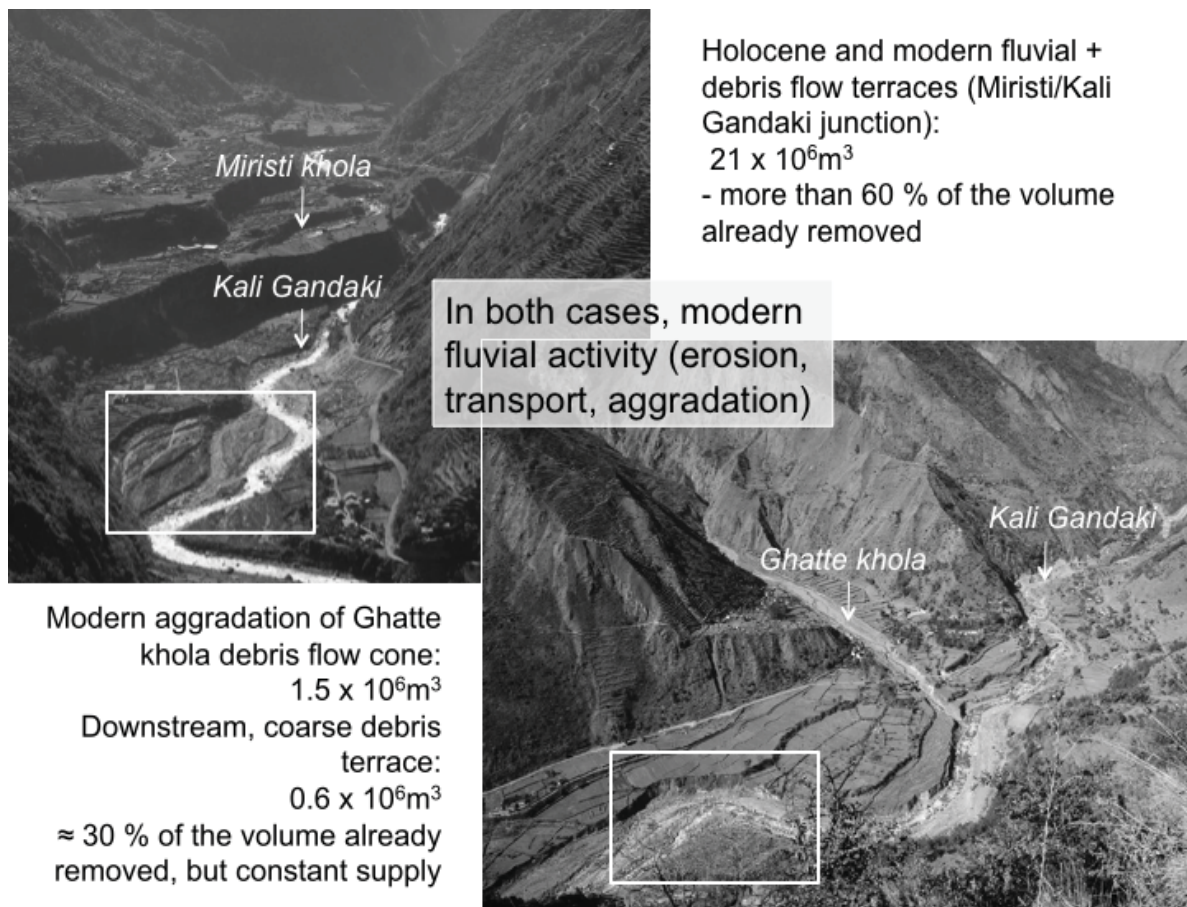


Fig. 9: Sediment removal affects both Holocene terraces of the Miristi-Kali Gandaki confluence, and the active Ghatte khola junction fan with the Kali Gandaki.

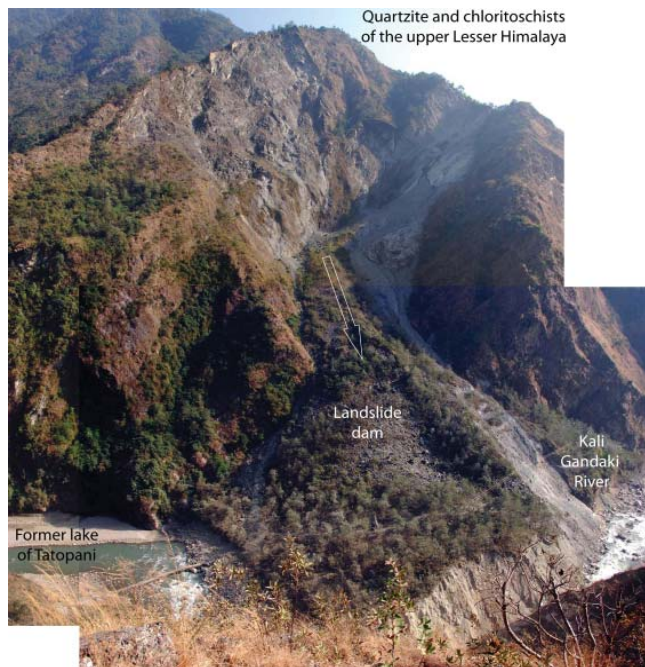


Fig. 10: The Tatopani landslide and the remnants of the backwater lake upstream (left).

the Kali Gandaki across the dam ($0.2 \times 10^6 \text{ m}^3$). We showed that the lake breaching was not catastrophic but progressive (it lasted approximately 3 hours), resulting in an increasing injection of both coarse and fine solid discharge that partly aggraded downstream in the form of a sedimentary wedge or prism, and encroached downstream on the alluvial plain as the landslide breach further enlarged. Less than 1 km-long, this accumulation represented however no more than 10% of the debris removed from the breach: the largest blocks ($>4 \text{ m}^3$) are remnants of the sedimentary wedge and are still clustered near the landslide dam and eroded banks, whereas the remaining, finer particles were flushed away by the Kali Gandaki river. The resulting diversion of the river on its right bank, caused the undercutting of the Holocene terrace deposits and the partial removal of colluvium, hence revealing the evidence of former landslide dam outburst events (Fig. 11).

The 1998 event was very short in time: the breach of the dam represents debris removal of $66,666 \text{ m}^3/\text{hour}$. Over the next fifteen years, the landslide mass has been further affected by shallow translational slides during each rainy seasons, supplying a continuous flux of debris (mostly pulverized slates) to the Kali Gandaki river, yet very limited (~ 3 orders of magnitude lower) if compared to the 1998 event. Indeed, the “regular” monsoon high flows are insufficient to remove the larger boulder lags that are now armouring the channel bed, whereas the landslide mass is getting progressively stabilized by revegetation (*Alnus Nep. sp.*). Debris would

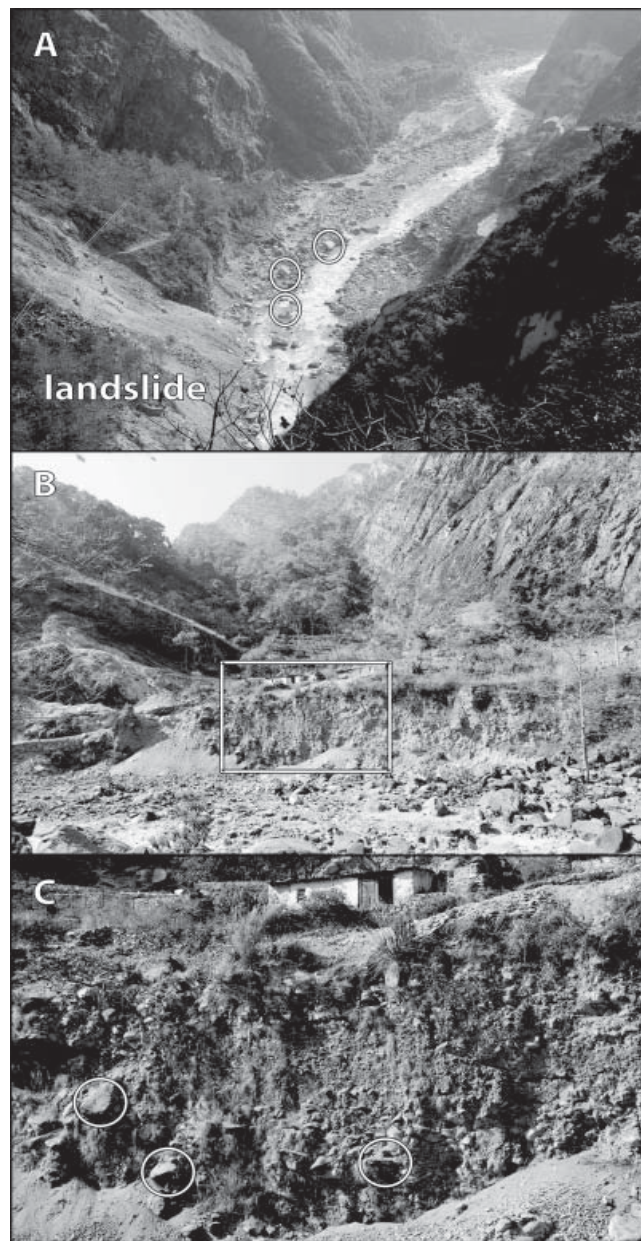


Fig. 11: Downstream effects of the Tatopani landslide dam erosion. (A) The entire width of the valley bottom was affected along 1500 m downstream, but the largest boulders (circles) were transported a few tens of meters only. (B) Eroded bank following the lake outburst: note the endangered houses and fields above the recent fan-terrace. (C) Detail (rectangle), showing large boulders embedded into the alluvial terrace material as evidence of former landslide dam outburst floods.

be remobilized again only by higher magnitude events, most often related to an off-normal supply of debris (i.e., landslides and/or debris flows) that might occur upstream, and generate debris pulses that would in turn increase the

density and the transport capacity, hence the efficiency of the flow downstream.

SEDIMENTARY BUDGET

We end up with a tentative sedimentary budget that encompasses many features from the oldest and the largest stores (Dhampu-Chhoya rock-avalanche, more than one billion cubic meters) to the most recent features (Tatopani landslide, Dana debris-flow) we observed along the middle Kali Gandaki valley (Fig. 12).

This figure is far from being complete, but shows events that developed at different time scales. More precisely, it gives an order of magnitude ($\sim 10\%$ error margin) of the importance of landsliding, a process that appears as the major debris supply to river channels. This sketch also highlights the fact that river damming by large scale, stable landslides at least doubles the possibility of sediment trapping in lakes (see the volume ratio between both landslides and lakes). At a finer scale, the adjustment of the longitudinal profile by retrogressive erosion provokes a progressive reconnection of the sediment cascades interrupted by dams. Exportation of the sediments of the landslide mass occurs first, followed by the exportation of the sediments stored within the aggradational plain created upstream of the dam. This second phase is probably associated with a significant rise in the sediment yield as sediments deposited upstream of the dam (silts in many cases) can be easily removed. The second stage may occur rapidly (probably a few millenia after the creation of the dam) and more than two thirds of the total amount of debris may finally be eroded away. Conversely, smaller, geologically “ephemeral” landslides reduce temporarily the width of the active channel, hence favouring a good connectivity between hillslope and river channel, therefore the rapid export of the material supplied by the slopes and/or small landslides tributary watersheds. More generally, it seems that high magnitude events reset the sediment cascade, and offset very temporarily the amount of sediment fluxes together with their morphological imprint.

More observations and measurements are requested to refine this general figure. This valley, as many other ones of this central part of the Himalayas, are certainly among the best places to test the sediment budget approach.

CONCLUDING REMARKS

Obtained results regarding erosional rates span over two- to three orders of magnitude that can best be explained by the type and frequency of erosional processes involved. In fact, within a given reach, most of erosion is accomplished as pulses triggered by landslide collapses and/or outburst

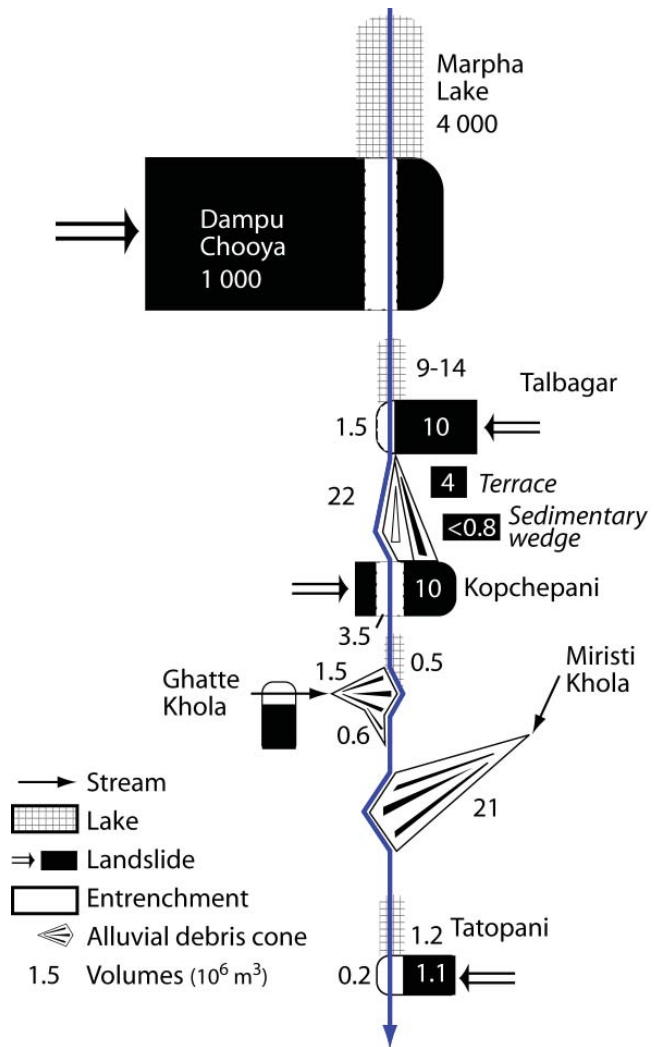


Fig. 12: Sedimentary budget of the Middle Kali Gandaki valley. The sediment stores appear in black boxes, whereas other numbers refer to volumes of sediment removal from initial stores (completed after Fort et al. 2009).

events, all the more rapid that debris involved is loose and erodible. Alternation of alluviation events and incision stages can then be reconstructed, and their relation with sismo-tectonic and/or climatic triggering events suggested, according to the time scale considered.

Our study suggests that landsliding plays a major role in the overall process of denudation and sediment transfer outward from the mountain zone. Debris supplied by the adjacent mountain slopes to the river channel are either directly carried away by the river or are a cause of blockage, the duration of which depends on the stability of the landslide dam or on the volume injected by tributaries at their junction

with the trunk river. In all cases there is an efficient sediment trapping. Yet, we have also seen that as soon as the blockage fails, the removal of debris can be extremely rapid, then followed by a more regular mode of debris transfer. Indeed, control factors on sediment fluxes act at local scale: dam material nature, bedrock lithology, channel slope, river discharge for a given period. More generally, it indirectly suggests that tectonic and related downcutting forcing is larger than climate forcing.

If large landslides contribute significantly to the denudation history of active mountain range (Hewitt et al. 2008), more frequent, medium to small scales landslides are in fact the largest suppliers of debris that may directly impact population. This suggests that in a very dynamic environment like the Himalayas, a sediment budget and fluxes approach is a useful tool for assessing and managing potential threats to human settlements and infrastructures that are increasingly developing along these Himalayan valley corridors.

ACKNOWLEDGEMENTS

Fieldwork in the Himalayas was supported by various CNRS and Paris-Diderot University research grants to M. F. during the last 35 years, and by PRODIG grants to M.F. and E.C in 2007. Dating facilities were provided by, CEREGE-ASTER Laboratory (Aix-en-Provence) and its director D. Bourlès, who deserve special thanks. The Tatopani example was studied together with G. Arnaud-Fassetta (University Paris-Diderot) to whom we express our deep appreciation. Warmest thanks go to M. F. porters Man Bahadur Mangar, Gopal Mangar and Iman Singh Lama, to the many villagers who provided information on past geomorphic events, and to Gopal K. Bashyal who was in the field with M. F. in 2000. We also thanks the many friends and colleagues of Kathmandu Institutions (Department of Mines and Geology, Sismology Laboratory, Geology at Tri-Chandra Campus Tribhuvan University, Geography and Geology Departments at Kirtipur University) for stimulating discussions and exchanges, with a special mention to Soma Nath Sapkota (DMG, SismoLab) and Lalu Paudel (Geology, Kirtipur University) for their support.

REFERENCES

- Andermann, C., Crave, A., Cloaguen, R., Davy, P. and Bonnet, S., 2012, Connecting source and transport: Suspended sediments in the Nepal Himalayas. *Earth and Planetary Science Letters*, v. 351-352, pp. 158-170.
- Baade, J., Lang, A., Mäusbacher, R. and Wagner, G. A., 1998, Quaternary lake deposits in the Thakkhola Graben, Mustang, Nepal. *Geological Bulletin, University of Peshawar*, v. 31, pp. 22-23.
- Baade, J., 2000, *Landschaftswandel im Thakkhola. Untersuchungen zur Landschaftsgenese im semi-ariden Hochgebirge Nepals seit dem Jungpleistozän. Habilitationsschrift, Chemisch-Geowissenschaftliche Fakultät, Friedrich-Schiller-Universität Jena.* 240 p.
- Burchfield, B. C., Chen, Z., Hodges, K. V., Liu, Y., Royden, L. H., Deng, C. and Xu, J., 1992, The South Tibetan Detachment System, Himalayan orogen: Extension contemporaneous with and parallel to shortening in a collisional mountain belt. *Geol. Soc. of America, Boulder, Colorado*, 41p.
- Campbell, D. and Church, M., 2003, Reconnaissance sediment budgets for Lynn Valley, British Columbia: Holocene and contemporary time scales. *Canadian Journal of Earth Sciences*, v. 40, pp. 701-713.
- Colchen, M., Le Fort, P. and Pecher, A., 1986, *Recherches géologiques dans l'Himalaya du Népal: Annapurna-Manaslu-Ganesh Himal.* CNRS Editions, Paris, 136 p.
- Dollfus, O. and Usselman, P., 1971, Aspects géomorphologiques de la vallée de la Kali Gandaki entre Jomosom et la confluence de la Modi Khola. In *Recherches géologiques dans l'Himalaya du Népal, région de la Thakkhola.* P. Bordet et al., CNRS Editions, Paris, pp. 179-186.
- Fort, M., 1974, *Données préliminaires sur la morphogenèse quaternaire de la vallée de la Kali Gandaki (Népal Central).* May 1974 Field Report CNRS, Lab. Géogr. Phys. Université Paris 753p (unpublished).
- Fort, M., 1980, Les formations quaternaires lacustres de la basse Thakkhola (Himalaya du Népal) : intérêt paléogéographique, néotectonique et chronologique. *C-R. Acad. Sciences Paris*, v. 290, pp. 171-174.
- Fort, M., 1987a, Sporadic morphogenesis in a continental subduction setting: an example from the Annapurna Range, Nepal Himalaya. *Zeit. für Geomorph., Suppl.-Bd.*, v. 63, pp. 9-36.
- Fort, M., 1987b, Geomorphic and Hazards mapping in the dry, continental Himalaya: 1:50,000 maps of Mustang District, Nepal. *Mountain Research and Development*, v. 7, pp. 222-238.
- Fort, M., 1993, *Etude géomorphologique d'une chaîne de collision intracontinentale (Himalaya du Népal, Transversale des Annapurnas).* State Doctoral Thesis, Université Paris 7, 702 pp., 149 fig. (+ 2 attached Geomorphological and Natural Hazards maps).
- Fort, M., 2000, Glaciers and Mass wasting processes: their influence in the shaping of the Kali Gandaki valley (Higher Himalaya of Nepal). *Quaternary International*, v. 65/66, pp. 101-119.
- Fort, M., 2004, Quaternary glaciation in the Nepal Himalaya. In: Ehlers, J. and Gibbard, P. L. (eds). *Quaternary glaciations-Extent and chronology. Part III: South America, Asia,*

- Africa, Australia, Antarctica. Developments in Quaternary Science, vol. 2c, Amsterdam, Elsevier, 261-278.
- Fort M., 2011, Two large late Quaternary rock slope failures and their geomorphic significance, Annapurna Himalayas (Nepal). *Geografia Fisica e Dinamica Quaternaria*, v. 34(1), pp. 5-14.
- Fort, M., Cossart E. and Arnaud-Fassetta, G., 2009, Interactions between unstable mountain slope and Kali Gandaki River: a sedimentary budget approach. In: J.-Ph. Malet, A. Remaitre & T. Bogaard (Eds) : « Landslide processes: from geomorphologic mapping to dynamic, CERG Editions, Strasbourg, pp. 25-30.
- Fort, M., Cossart E. and Arnaud-Fassetta G., 2010a, Catastrophic landslides and sediment budgets. In: I. Alcantara Ayala and A. Goudie (eds): *Geomorphology, Hazards and Disaster Prevention*. Cambridge University Press, ch. 7, pp. 75-86.
- Fort, M., Cossart, E. and Arnaud-Fassetta, G., 2010b, Hillslope-channel coupling in the Nepal Himalayas and threat to man-made structures: the middle Kali Gandaki valley. *Geomorphology*, v. 124, pp. 178-199.
- Fort, M. and Peulvast, J. P., 1995, Catastrophic mass-movement and morphogenesis in the peri-tibetan ranges, examples from West Kunlun, East Pamir and Ladakh. in: *Steeplands* (O. Slaymaker ed.), Wiley & Sons. pp. 171-198.
- Fort, M., Shrestha, B. L. and White, P. G., 1987. 1:50,000 geomorphic hazards mapping in Nepal: tests in Gorkha, Myagdi and Mustang Districts. *Himalayan Research and Development, Nainital*, v. 4 (2), pp. 1-12.
- Gabet, E. J., Burbank, D. W., Putkonen, J. K., Pratt-Sitaula, B. A. and Ojha, T., 2004. Rainfall thresholds for landsliding in the Himalayas of Nepal. *Geomorphology*, v. 63, pp. 131-143.
- Gaillardet, J. and Galy, A., 2008, Atmospheric science. Himalaya-carbon sink or source? *Science*, v. 320 (5884), pp. 1727-8.
- Galy, A. and France-Lanord, C., 1999, Weathering processes in the Ganges-Brahmaputra basin and the riverine alkalinity budget. *Chem. Geology*, v. 159, pp. 31-60.
- Garzanti, E., Vezzoli, G., Andò, S., Lavé, J., Attal M., France-Lanord, C. and DeCelles, P., 2007, Quantifying sand provenance and erosion (Marsyangdi River, Nepal Himalaya). *Earth and Planetary Science Letters*, v. 258, pp. 500-515.
- Godin, L., 2003, Structural evolution of the Tethyan sedimentary sequence in the Annapurna area, central Nepal Himalaya. *Journal of Asian Earth Sciences*, v. 22, pp. 307-328.
- Hewitt, K., 2002, Postglacial landforms and sediment associations in a landslide-fragmented river system: the Transhimalayan Indus stream, Central Asia. In: Hewitt, K., Byrne, M. L., English, M., Young, G. (eds.), *Landscapes of transition, Landform assemblages and transformations in cold regions*, 63-91. Dordrecht, Kluwer, pp. 3-91.
- Hewitt, K., Clague J. J., Orwin, J. F., 2008, Legacies of catastrophic rock slope failures in mountain landscapes. *Earth Science Reviews*, v. 87, pp. 1-38.
- Hurtado, J. M., Hodges, K. V. and Whipple, K. X., 2001, Neotectonics of the Thakkhola graben and implications for recent activity on the South Tibetan fault system in the central Nepal Himalaya. *GSA Bulletin*, v. 113(2), pp. 222-240.
- Iwata, S., 1984, Relative chronology of Holocene and Late Pleistocene moraines in the Nepal Himalayas. In: Li J.J. (ed.), *Evolution of Mountain Glaciers and the Quaternary Glaciation*, Lanzhou, pp. 47-57.
- Iwata, S., 1987, Mode and rate of uplift of the central Nepal Himalaya. *Z. Geomorphol., Suppl.* 63, 37-49.
- Iwata, S., Yamanaka H. and Yoshida M., 1982, Glacial landforms and river terraces in the Thakkhola region, central Nepal. *Journal of Nepal Geological Society*, v. 2, pp. 81-94.
- Métivier, F., Gaudemer Y., Tapponnier, P. and Klein, M., 1999, Mass accumulation rates in Asia during the Cenozoic. *Geophysical Journal International*, v. 137(2), pp. 280-318.
- Milliman, J. D. and Meade, R. H., 1983, Geomorphic/tectonic control of sediment discharge to the ocean: the importance of small mountainous rivers. *J. Geol.*, v. 100, pp. 525-544.
- Monecke, K., Winsemann, J. and Hanisch, J., 2001, Climatic response of Quaternary alluvial deposits in the upper Kali Gandaki valley (West Nepal). *Global and Planetary Change*, v. 28, pp. 293-302.
- Owen, L. A., 2009, Latest Pleistocene and Holocene glacier fluctuations in the Himalaya and Tibet. *Quaternary Science Reviews*, v. 28, pp. 2150-2164.
- Pratt-Sitaula, B., Burbank, D. W., Heimsath, A. M. and Ojha, T., 2004, Landscape disequilibrium on 100-10,000 year scales, Marsyangdi River, Nepal, central Himalaya. *Geomorphology*, v. 58, pp. 223-241.
- Pratt-Sitaula, B., Garde, M., Burbank, D. W., Oskin, M., Heimsath, A. and Gabet, E., 2007, Bedload-to-suspended load ratio and rapid bedrock incision from Himalaya landslide-dam lake record. *Quaternary Research*, v. 68, pp. 111-120.
- Sikrikar, S. M. and Piya, B., 1998, Field report on Tatopani landslide of 10 Aswin 2055, Tatopani village, Myagdi District. Department of Mines and Geology, Lainchaur, Katmandu, 26 p. (unpublished)
- Slaymaker, O., 2003, The sediment budget as conceptual framework and management tool. *Hydrobiologia*, v. 494, pp. 71-82.
- Summerfield, M. A. and Hulton, N. J., 1994, Natural controls of fluvial denudation rates in major world drainage basins. *J. Geophys. Res.*, v. 99 (B7), pp. 13871-13883.
- Upreti, B. N. and Yoshida, M., 2005, *Geology and Natural Hazards along the Kaligandaki Valley, Nepal*. Guidebook for Himalayan Trekkers, Series N°1, Department of Geology, Tri-Chandra Campus, Tribhuvan University, Kathmandu Nepal, 165p.

- Voelk, H. R., 2000, The 1998 Tatopani landslide in the Kali Gandaki valley of Western Nepal: cause and relation to mass rock creep. *Journal of Nepal Geological Society*, v. 22, pp. 405-412.
- Weidinger, J. T., 2006, Predesign, failure and displacement mechanisms of large rockslides in the Annapurna Himalayas, Nepal, *Engineering Geology*, v. 83, pp. 201-216.
- White, P. G., Fort, M. and Shrestha, B. L., 1987, Prototype 1:50 000 scale mountain hazard mapping in Nepal. *Journal of Nepal Geological Society*, v. 4 (1-2), pp. 43-53.
- Yamanaka, H. and Iwata, S., 1982, River terraces along the Middle Kali Gandaki and Marsyangdi Khola, Central Nepal. *Journal of Nepal Geological Society*, v. 2, Special Issue, pp. 95-111.
- Zech, R., Zech, M., Kubik, P. W., Kharki, K. and Zech, W., 2009, Deglaciation and landscape history around Annapurna, Nepal, based on ^{10}Be surface exposure dating, *Quaternary Science Reviews*, v. 28(11- 12), pp.1106–1118.